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A METHOD OF CORRECTING P-WAVE MAGNITUDES FOR THE EFFECT OF EARTHQUAKE FOCAL MECHANISM

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13. ABSTRACT

This paper presents a methodology for correcting body-wave magnitudes for the effect of focal mechanism in a routine manner. The method requires a knowledge of the prevailing or dominant mechanism for a geographic region, from which tables are constructed which enable one to make the necessary correction. Included in the paper are tables for Aleutian Island, Kamchatka and mid-Atlantic Ocean earthquakes.

From a study of seven earthquakes, it is concluded that the present method gives essentially the same average magnitude with the same standard deviation as a more exact method of correcting for the focal mechanism. The latter method uses the focal-mechanism parameters of the earthquake, which must be determined independently for each earthquake.

The existing distribution of seismograph stations is such that transform-fault earthquakes of the mid-Atlantic Ocean will consistently have their P-wave magnitudes underestimated by about 0.2 magnitude units, if no correction is made for the focal mechanism. On the other hand, P-wave magnitudes of earthquakes in Kamchatka and south of the axis of the Aleutian Trench will be overestimated by about 0.2 units.

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INTRODUCTION

For a study of earthquake statistics, it is desirable to classify seismic events according to their relative and absolute size. The concept of magnitude, as introduced by Richter (1935), first made this classification possible. However, for the study to be meaningful, it is necessary to make the determination of earthquake magnitude independent of anomalous propagation conditions and of the existing distribution of seismograph stations.

For a uniform source located in an Earth model which is laterally homogeneous, Gutenberg and Richter's (1956) formula for the body-wave magnitude, m_b, can be written as

$$m_b = \log (A/T) + \bar{Q}(h, \Delta) \tag{1}$$

where A is ground amplitude, T its corresponding period, h the focal depth and Δ the epicentral distance. Departures from this ideal case are caused by lateral heterogeneity in velocity and by the focal mechanism. The former includes effects at the station and the source, which may be large if the ray paths cross descending lithospheric plates (Jacob, 1970; Toksöz *et al.*, 1971). The effects of focal mechanism can cause a rather large under- or overestimation of the magnitude, depending upon the distribution of seismograph stations used in calculating the magnitude (von Seggern, 1970).

Jansch (1968) and Chandra (1970) proposed methods of improving the determination of body wave magnitude by considering the effect of the radiation pattern on the

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recorded P-wave amplitudes. Chandra's (1970) method requires prior knowledge of the focal-mechanism parameters of the earthquake. Because such data generally are not available, the method cannot be applied on a routine basis. In Jarosch's (1968) method, a focal-mechanism solution is calculated from the signs of the first P motion and the amplitudes of P. The amplitudes of P, then, are corrected for the radiation pattern and used to determine the body-wave magnitude. A limitation of the method for practical purposes is that it requires a large amount of data well distributed in azimuth, signs of first P motion, and a rather extensive set of calculations. The purpose of the present study is to develop a simple method which routinely can be used to obtain body-wave magnitude estimates that are corrected for the focal mechanism. To this end, the concept of a dominant focal mechanism, representative of the mechanism of earthquakes in a given hypocentral region, is introduced.

Theory

The P-wave displacement, u, on the surface of a focal sphere of radius R, owing to a double-couple source with forces $K(t)$, is given by (Bessonova *et al.*, 1960; Stauder, 1962)

$$u = 2xyK'(t - R/\alpha)/4\pi\rho\alpha^3R^3 \tag{2}$$

where ρ is the density, α the P-wave velocity and $K'(t)$ the time derivative of $K(t)$. The quantities x and y depend upon the orientation of the forces of the couple and the location of the point on the surface of the focal sphere at which the particle displacement is being calculated. Equations for x and y are given in the Appendix.

All the terms in equation (2) except for $2xy$ are constant on the surface of the focal sphere. Thus, the observed P-wave amplitudes, when divided by $2xy$, are corrected in a relative sense for the earthquake radiation pattern. From the equations given in the Appendix, it can be shown that the absolute value of $2xy$ varies from zero to unity. By a simple integration, it further can be shown that the average value of $|2xy|$ over the surface of the focal sphere is $4/3\pi$ or approximately 0.424. Thus, in order to correct the observed amplitude for the effect of the focal mechanism in an absolute sense, it is necessary to multiply the amplitude by $0.424/2xy$. This will reduce the observed P-wave amplitude from a double-couple source to that which it would be from a spherically symmetric source, whose hypothetical amplitude is the average over the surface of the focal sphere of the actual amplitudes from the double-couple source.

For body-wave magnitude determinations, it is best to use data from stations distant from nodal lines, i.e., with large $2xy$ factors. Not only are amplitudes on the seismogram larger and less subject to errors of measurement, but, also for such stations, small errors in the focal-mechanism parameters will have a minimal effect upon the value of $2xy$ used in reducing the amplitude for the radiation pattern of the earthquake.

Earthquake foci located in a given region tend to have similar focal mechanisms, which is in keeping with the theory of plate tectonics (Isacks *et al.*, 1968). On the hypothesis that characteristic foci exist for given hypocentral regions, focal-mechanism parameters for a dominant or average mechanism of a region can be determined. From this the $2xy$ factor can be calculated for each seismograph station, and a list of $2xy$ factors can be compiled for all seismograph stations for any earthquake in this region. The list of $2xy$ factors is utilized in two ways. First, it is used to verify or disprove that the actual focal mechanism of the earthquake conforms to the dominant one (Syed,

Kisslinger and Nuttli, 1971). Second, if it is established that the focal mechanism is normal, the list is used to select those stations which have *P* waves of large amplitude and, therefore, are best suited for magnitude determination.

Consider the sublist of seismograph stations for which $2xy > 0.424$. Call $(m_b)_i$ the magnitude, corrected for the focal mechanism, for the i'th of n such stations for which *P*-wave amplitude data are available. Then

$$(m_b)_i = \log \frac{(A/T)_i}{(2xy/0.424)_i} + \bar{Q}_i .$$

The uncorrected magnitude, $(m_{b,u})_i$, is given by

$$(m_{b,u})_i = \log (A/T)_i + \bar{Q}_i$$

from which it follows that the magnitude calculated from the i'th station is

$$(m_b)_i = (m_{b,u})_i - \log (2xy/0.424)_i .$$

The average magnitude, based upon the data of n stations, is

$$m_b = \left(\sum_{i=1}^{n} (m_b)_i\right) \Big/ n = \left(\sum_{i=1}^{n} (m_{b,u})_i\right) \Big/ n - \left(\sum_{i=1}^{n} \log (2xy/0.424)_i\right) \Big/ n. \qquad (3)$$

The first term on the right-hand side of equation (3) is the magnitude of the earthquake, uncorrected for the focal mechanism. It may be called $m_{b,u}$. The second term, called *F*, is approximately equal to

$$-\left(\sum_{i=1}^{N} \log (2xy/0.424)_i\right) \Big/ N, \qquad n \leq N$$

where *N* is the total number of the stations of the sublist for which $2xy > 0.424$. *F* is a constant for all earthquakes of the region having the dominant focal mechanism, and, thus, may be called the regional correction factor, as is suggested by rewriting equation (3) as

$$m_b = m_{b,u} + F. \qquad (4)$$

Equation (4) provides a simple procedure for calculating magnitudes which are corrected for the effects of the focal mechanism, once the $2xy$ factors and the value of *F* are calculated for a group of seismograph stations and a given region. One merely finds the average $m_{b,u}$ from the data of those stations for which $2xy > 0.424$ and adds to this quantity the tabulated value of *F*.

Selection of Stations

Published focal mechanism solutions of earthquakes in the Aleutian Islands, Kamchatka and the mid Atlantic Ocean have been compiled. For the Aleutian Islands, it was found that the considered earthquakes, on the basis of their focal mechanisms, divide into three groups and that these groups are geographically distinct. All of the earthquakes examined for the Kamchatka region, however, could be represented by

a single dominant mechanism. For the mid-Atlantic Ocean, the mechanisms are of the tensional type, as associated with ridges, or of the strike-slip type, as associated with transform faults along fracture zones.

Aleutian Islands. The first group (Group 1) of Aleutian Island earthquakes is based on the common focal-mechanism solutions of 12 earthquakes in the Rat Islands. The locations of these earthquakes, as well as those of the other Aleutian groups, are shown in Figure 1. Stauder (1968a) and Stauder and Bollinger (1964) determined the focal-mechanism parameters of these earthquakes. The averages of these parameters, which are taken to be those of the dominant focal mechanism, are: X-axis (azimuth 326°3 ± 5°0, plunge 14°3 ± 6°2), Y-axis (azimuth 169°3 ± 29°2, plunge 72°3 ± 5°7). The X and Y axes are the axes of the forces of the double-couple mechanism. Because the dominant focal-mechanism parameters have been obtained by taking the arithmetic

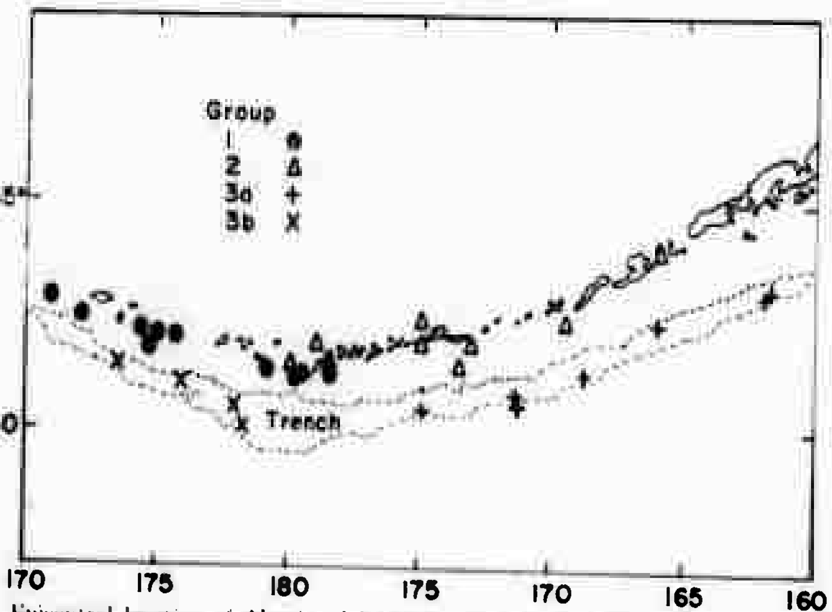

FIG. 1. Epicentral location of Aleutian Island earthquakes, with grouping according to focal mechanism.

average of the 12 earthquakes of this region, the resulting X and Y axes are not exactly orthogonal. For example, in this case, orthogonality can be achieved by increasing the plunge of the Y axis by 2°2. Any or all of the four parameters could be changed, of course, to make the X and Y axes mutually perpendicular.

The focal mechanism of earthquakes of Group 1, Aleutian Islands, corresponds to that for which one P wave nodal plane is steeply dipping and the other is almost horizontal. Assuming the latter to be the fault plane, Stauder (1968a) showed that the motion is characteristic of thrust faulting along a plane dipping at about 15° to 20° under the island arc. The relative motion of the underthrust block is toward the northwest.

For this and the other groups considered, $2ry$ factors were calculated for all the WWSSN and Saint Louis University seismograph stations, as well as station D 1 of LASA, which are in the epicentral distance range of 25° to 100°. The results are given in Table 1. The hypocenter of the earthquake of February 6, 1965 (52°1 N, 173°7 E)

was taken to be representative of the earthquakes of Group 1, Aleutian Islands, for the purpose of calculating epicentral distances, angles of incidence at the focus and azimuths of the great circle paths from the epicenter to the stations.

The first set of stations in Table 1, for which $2xy > 0.424$, correspond to those that are to be used for magnitude determinations. It can be observed that the only stations in the United States which will have larger-than-average P amplitudes are OGD and WES, whereas, almost all European and Asian stations will have large values. Thus, a P-wave magnitude for an earthquake in this region, if it principally is based upon data from United States stations and if no focal-mechanism correction is made, will be underestimated. The minus signs preceding the $2xy$ factor for some stations indicate

TABLE 1

$2xy$ AND F* FACTORS FOR ALEUTIAN ISLANDS, GROUP 1 EARTHQUAKES

Station	2xy	Station	2xy	Station	2xy	Station	2xy
AKU	0.798	MSH	0.936	ADE	0.183	HNR	−0.127
AQU	0.864	NDI	0.904	AFI	−0.367	JCT	0.137
ATU	0.882	NHA	0.660	ALQ	0.093	LON	0.071
BAG	0.579	NOR	0.803	ATL	0.305	LPS	0.481
BEC	0.424	NUR	0.906	BHP	0.255	LUB	0.131
CCG	0.717	OGD	0.430	BKS	−0.069	MDS	0.323
CMC	0.496	PHA	0.710	BLA	0.362	MHT	0.231
COP	0.800	POO	0.857	BLC	0.369	MNN	0.307
ESK	0.835	PTO	0.788	BOG	0.276	MUN	0.359
GDH	0.693	QUE	0.945	BOZ	0.455	ONF	0.267
HKC	0.693	SEO	0.725	CAR	0.358	PMG	0.066
HLW	0.882	SHI	0.907	COR	0.022	QUI	0.224
HOW	0.844	SHL	0.848	CTA	0.090	RAB	−0.024
IST	0.902	SNG	0.690	DI	0.216	RAB	−0.302
JER	0.894	STU	0.866	DAL	0.184	RCD	0.242
KEV	0.896	TAB	0.928	DAV	−0.254	RIV	0.079
KIP	−0.678	TOL	0.804	DUG	0.073	ROL	0.266
KOD	0.805	TRI	0.871	FLO	0.285	SCP	0.404
KON	0.872	UME	0.895	GEO	0.398	SHA	0.255
LAH	0.915	VAL	0.806	GIE	0.135	SLM	0.274
MAL	0.797	WES	0.464	GOL	0.144	TAU	0.108
MAN	0.560			GSC	−0.032	TUC	0.017
MAT	0.580	AAM	0.366	GUA	0.162	WEL	−0.045

* F, Regional correction factor = −0.25.

that the direction or sense of the first P motion at those stations will be opposite that at all other stations.

The earthquakes of Group 2 of the Aleutian Islands extend along the arc from the Andreanoff to the Fox Islands, as can be seen in Figure 1. An average focal mechanism is calculated from the mechanism parameters of nine earthquakes, as determined by Stauder and Udias (1963). Its values are: X-axis (azimuth 303°8 ± 11°1, plunge 23°0 ± 7°7), Y axis (azimuth 191°1 ± 7°1, plunge 36°8 ± 5°2).

Table 2 presents the $2xy$ and F factors for Group 2, Aleutian Island earthquakes. Almost all of the stations with $2xy > 0.424$ are in Asia or the southwest Pacific. Thus P wave magnitude estimates for earthquakes in this region which rely heavily upon United States and European data will be too small, unless a correction for the focal mechanism is made.

The earthquakes of Group 3 of the Aleutian Islands are located in a narrow band just

to the south of the axis of the Aleutian Trench, as shown in Figure 4. Stauder (1968b) determined focal mechanisms for 11 earthquakes of this group. Although the P-wave nodal planes dip at about the same angle for all these earthquakes, their strike directions change as the orientation of the axis of the trench changes. For this reason, it was decided to subdivide the group of earthquakes into two parts, a western (Group 3b) and an eastern (Group 3a). Average focal mechanism parameters for Group 3a are: X-axis (azimuth 156°9 ± 12°4, plunge 42°9 ± 7°4), Y-axis (azimuth 350°1 ± 31°4, plunge 39°1 ± 7°3). For Group 3b they are: X-axis (azimuth 16°0 ± 13°5, plunge 40°0 ± 1°9), Y-axis (azimuth 231°0 ± 7°8, plunge 43°7 ± 3°8). Both P-wave nodal planes dip at about 45°, and their strikes are approximately parallel to the trend of the trench. The earthquakes are of extensional character, with the axis of tension perpendicular to the axis of the trench.

TABLE 2

$2xy$, AND F* FACTORS FOR ALEUTIAN ISLANDS, GROUP 2 EARTHQUAKES

Station	$2xy$	Station	$2xy$	Station	$2xy$	Station	$2xy$
ADE	0.626	SHL	0.742	COR	−0.061	NOR	0.069
BAG	0.894	TAB	0.474	DI	0.010	NUR	0.269
CTA	0.645	TAU	0.556	DAL	0.017	OGD	0.098
GUA	0.858			HUG	−0.041	ONF	0.018
HKC	0.872	AAM	0.068	ESK	0.235	PHA	0.043
HLW	0.436	AFI	0.189	FLO	0.044	PTO	0.280
HNR	0.556	AKU	0.152	GDH	0.074	QUI	0.133
HOW	0.734	ALQ	−0.029	GEO	0.091	RAR	0.131
JER	0.454	AQU	0.342	GIE	0.092	RCD	0.011
KOD	0.705	ATU	0.391	GOL	−0.010	ROL	0.039
LAH	0.625	ATL	0.070	GSC	−0.093	SCP	0.087
MAN	0.892	BEC	0.134	IST	0.396	SHA	0.053
MSH	0.532	BHP	0.117	KEV	0.202	SLM	0.017
NDI	0.563	BKS	0.099	KIP	−0.314	STU	0.301
NHA	0.819	BLA	0.081	KON	0.242	TOL	0.297
PMG	0.691	BLO	0.057	LON	−0.038	TRI	0.331
POO	0.670	BOG	0.144	LPS	0.059	TRN	0.175
QUE	0.596	BOZ	−0.008	LUB	−0.008	TUC	−0.060
RAB	0.671	CAR	0.160	MAL	0.304	UME	0.237
RIV	0.562	CCG	0.038	MDS	0.050	VAL	0.227
SEO	0.878	CMC	0.012	MHT	0.024	WEL	0.403
SHI	0.534	COP	0.272	MNN	0.010	WES	0.103

* F, Regional correction factor = −0.20.

Tables 3 and 4 contain the names of the seismograph stations to be used for P-wave magnitude determination for earthquakes of Group 3a and 3b, respectively, of the Aleutian Islands. For Group 3a earthquakes, all except three stations in the distance range 25° to 100° have $2xy > 0.424$. This indicates that the geometry of the focal mechanism is such that the ray paths to most seismograph stations will intersect the focal sphere at points where the P-wave amplitudes are greater than the average over the surface of the focal sphere. Thus, P-wave magnitudes for earthquakes of this region which are uncorrected for the effects of focal mechanism will be too large. Note also for Group 3a and 3b earthquakes that all $2xy$ factors have the same sign.

Kamchatka. On the basis of the focal mechanism solutions of 16 earthquakes, as given by Udias and Stauder (1964), it appears that all earthquakes located on the east

coast of the Kamchatka peninsula have similar mechanisms. Figure 2 shows the location of the earthquakes. The dominant focal-mechanism parameters for this group of earthquakes are: X-axis (azimuth 317°.3 ± 10°.5, plunge 40°.8 ± 4°.2), Y-axis (azimuth 132°.7 ± 13°.1, plunge 45°.5 ± 4°.6).

According to Udias and Stauder, the characteristic feature of the focal-mechanism solutions of this group of earthquakes is a steeply-inclined, near-vertical axis of tension. The P-wave nodal planes dip about 45° each and strike in a northeast direction. In most cases, the pressure axis is normal to the direction of the coast of Kamchatka.

The list of stations with their $2xy$ factors for Kamchatka earthquakes is given in Table 5. Almost all stations in the distance range of teleseismic P have $2xy > 0.424$,

TABLE 3

$2xy$, AND F* FACTORS FOR ALEUTIAN ISLANDS, GROUP 3A EARTHQUAKES

Station	2xy	Station	2xy	Station	2xy	Station	2xy
AAM	0.741	DUG	0.656	MAN	0.605	SCP	0.756
ADE	0.663	ESK	0.635	MDS	0.727	SEO	0.468
AKU	0.574	FLO	0.738	MHT	0.722	SHA	0.762
ALQ	0.676	GDH	0.550	MNN	0.715	SHI	0.679
AQU	0.595	GEO	0.761	MSH	0.633	SHL	0.614
ATU	0.697	GIE	0.773	NDI	0.638	SLM	0.738
ATL	0.767	GOL	0.686	NHA	0.640	STU	0.665
BAG	0.601	GSC	0.604	NNA	0.806	TAB	0.653
BEC	0.800	GUA	0.502	NUR	0.547	TOL	0.735
BHP	0.809	HKC	0.586	OGD	0.760	TRI	0.680
BKS	0.589	HNR	0.498	ONF	0.749	TRN	0.843
BLA	0.767	HOW	0.644	PDA	0.771	TUC	0.615
BLO	0.749	IST	0.674	PMG	0.567	UME	0.530
BOG	0.825	JER	0.695	POO	0.687	VAL	0.668
BOZ	0.674	KEV	0.462	PTO	0.737	WEL	0.616
CAR	0.836	KOD	0.698	QUE	0.654	WES	0.759
CCG	0.455	KON	0.586	QUI	0.815		
CMC	0.509	LAH	0.626	RAB	0.520	AFI	0.407
COP	0.611	LON	0.631	RAR	0.461	KIP	0.052
COR	0.614	LPS	0.769	RCD	0.695	NOR	0.397
DH	0.686	LUB	0.702	RIV	0.639		
DAL	0.721	MAL	0.748	ROL	0.734		

* F, Regional correction factor = −0.20.

which indicates that relatively large P-wave amplitudes are to be expected at all stations. As for Group 3, Aleutian Island earthquakes, all of the stations in Table 5 have the same sign for the $2xy$ factor.

Mid-Atlantic Ocean. The mid-Atlantic Ocean earthquakes divide into two groups, tension-type associated with the ridge and strike-slip associated with the transform faults of the fracture zones. Figure 3 shows the location of 20 earthquakes for which published focal mechanism solutions are available.

Group 1 of the mid-Atlantic consists of earthquakes of the transform-fault type. Sykes (1967) and Stauder and Bollinger (1966) gave focal mechanism solutions for seven earthquakes of this group. Their average parameters are: X-axis (azimuth 274°.6 ± 7°.4, plunge 6°.1 ± 7°.6), Y-axis (azimuth 4°.0 ± 7°.7, plunge 2°.6 ± 11°.1).

Two problems were encountered in preparing a list of stations to be used for magnitude determination for Atlantic Ocean earthquakes. First, the orientation of the

nodal planes is such that almost all P waves arriving at teleseismic distances will have small $2xy$ factors (relatively small P amplitudes). Thus, one is forced to use data from stations with $2xy$ factors less than the average of the values over the surface of the focal sphere. For this special group, we will require only that $2xy > 0.20$. The regional correction factor, F, will accordingly be positive.

The second problem arises from the fact that the epicenters of Group 1, mid-Atlantic earthquakes are spread over a large geographic area. Thus it is not possible to assign a "typical" epicenter for all earthquakes of this group. Because the $2xy$ factor depends upon epicentral distance and azimuth from the epicenter to the seismograph station as well as the focal-mechanism parameters, no single value of $2xy$ will apply to all earth-

TABLE 4

$2xy$ AND F* FACTORS FOR ALEUTIAN ISLANDS, GROUP 3B EARTHQUAKES

Station	$2xy$	Station	$2xy$	Station	$2xy$	Station	$2xy$
AAM	0.493	HLW	0.968	POO	0.959	AFI	0.422
AHE	0.634	HOW	0.907	PTO	0.841	ALQ	0.406
AKU	0.688	IST	0.944	QUE	0.980	BKS	0.321
AQU	0.905	JER	0.973	RAR	0.506	BOZ	0.320
ATU	0.942	KEV	0.783	RIV	0.590	CMC	0.273
ATL	0.531	KOD	0.938	ROL	0.472	COR	0.268
BAG	0.602	KON	0.815	SCP	0.529	DI	0.338
BEC	0.642	LAH	0.968	SEO	0.643	DUG	0.344
BHP	0.654	LPS	0.606	SHA	0.526	GOL	0.384
BLA	0.531	LUB	0.440	SHI	0.989	GSC	0.371
BLO	0.495	MAL	0.866	SHL	0.895	GUA	0.268
BOG	0.661	MAN	0.595	SLM	0.474	HNR	0.354
CAR	0.672	MDS	0.447	STU	0.870	KIP	0.313
CCG	0.493	MHT	0.433	TAB	0.976	LON	0.261
COP	0.847	MSH	0.983	TAU	0.619	MNN	0.417
CTA	0.510	MUN	0.704	TOL	0.861	PMG	0.422
ESK	0.798	NII	0.958	TRI	0.894	RAB	0.342
FLO	0.474	NHA	0.733	UME	0.819	RCD	0.362
GDH	0.524	NOR	0.596	VAL	0.787	TUC	0.441
GEO	0.545	OGD	0.544	WEL	0.592		
GIE	0.645	ONF	0.496	WES	0.559		
HKC	0.690	PDA	0.787				

* F, Regional correction factor $= -0.22$.

quakes of the group. The only way to handle this problem is to calculate sets of $2xy$ factors, each one of which applies only to epicenters in a limited range of latitude and longitude.

Table 6 applies to Group 1, mid-Atlantic earthquakes with epicenters from 7° to 11°N, 36° to 43°W. Similar tables can be prepared for Group 1 earthquakes with epicenters that fall outside these geographic limits. The stations are divided into sets, corresponding to $2xy$ being greater or less than 0.200. All stations in Africa and Europe, with the exception of those in Spain, belong to the second set, indicating that P-wave amplitudes at stations on those continents will be relatively very small.

Thirteen focal mechanism solutions, as given by Misharina (1964), were averaged to give the parameters of the dominant mechanism of Group 2, mid-Atlantic earthquakes. For these earthquakes, the tension axis is near horizontal and perpendicular to the ridge axis, and the pressure axis approximately horizontal and parallel to the ridge

axis. The average mechanism parameters are: X-axis (azimuth 222°7 ± 27°1, plunge 18°8 ± 8°3), Y-axis (azimuth 315°4 ± 27°0, plunge 20°4 ± 6°6). For this group of earthquakes, the stations in North and South America have $2xy$ factors greater than 0.424, with corresponding relatively large P-wave amplitudes.

Similar to Group 1, the earthquakes of this group can have a large geographic separation. For this reason, the computed $2xy$ factors are valid only for earthquakes occurring in a limited geographic region. As an example, Table 7 gives the list of $2xy$ factors for Group 2, mid-Atlantic earthquakes with epicenters between 49° to 56°N and 28° to 35°W.

APPLICATION OF THE METHOD

P-wave amplitudes are affected not only by the focal mechanism, but also by crust and upper-mantle structure near the source and the station. The conventional method

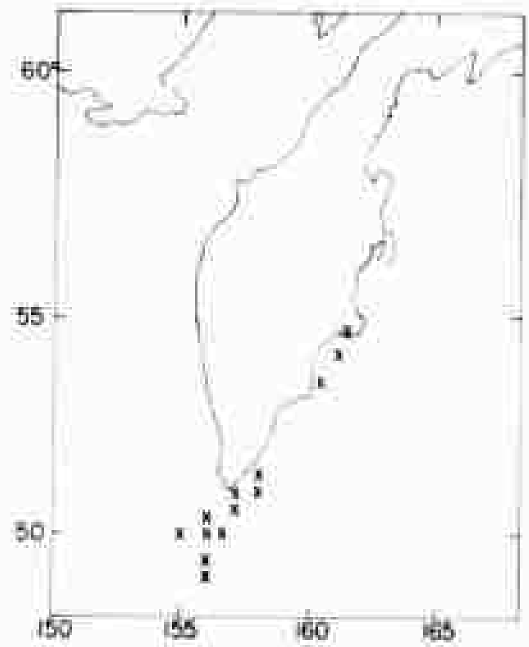

FIG. 2. Epicentral location of Kamchatka earthquakes.

of obtaining m_b utilizes A, T values obtained from short-period, vertical-component seismographs. However, long-period P waves are more coherent across an array than short-period ones, with their amplitudes and wave form exhibiting little dependence upon variations in geological structures beneath the array. Syed (1969) demonstrated this for LASA and Nuttli (1964), for the Saint Louis University network in the central United States. Therefore, a decision was made to use long-period P-wave amplitudes in the present study, in order to minimize the effects of crustal structure on the amplitudes and, thus, to emphasize the effects of the focal mechanism.

It further was decided to make use of the amplitude of the first half-cycle of the P-wave motion, rather than the maximum in the first three or more cycles, as is customary when short-period data are used. This reduces the complications owing to crustal effects at the station, including converted S waves and leaking mode PL waves. The measured amplitudes were "corrected" for the frequency response of the seismo

graph system, using response curves for steady state sinusoidal input. This procedure, although not exact, commonly is used in magnitude determinations because of its simplicity. Considering that it is the logarithm of A/T that is used in magnitude evaluation, the error introduced by this procedure probably is not significant.

Two sets of $Q(\Delta, h)$ tables were used in calculating m_b values. One is the widely used set of Gutenberg and Richter (1956). The second is a set calculated by Duda (1970), which was derived from the travel times of the 1968 Herrin P Tables under the assumption that there is no anelastic attenuation of P in the frequency range of interest. In general, average values of m_b obtained using the two sets of $\bar{Q}$ values agreed to the nearest one-tenth of a magnitude unit, but the standard deviations are smaller for the

TABLE 5

$2xy$ AND F* FACTORS FOR KAMCHATKA EARTHQUAKE

Station	$2xy$	Station	$2xy$	Station	$2xy$	Station	$2xy$
AAE	0.777	DAV	0.653	LUB	0.763	RIV	0.702
AAM	0.601	DUG	0.701	MAL	0.801	RCL	0.701
ADE	0.722	ESK	0.711	MAN	0.605	SCP	0.819
AFI	0.692	FLO	0.766	MDS	0.785	SHA	0.815
AKU	0.681	GDH	0.691	MHT	0.771	SHI	0.673
ALQ	0.730	GEO	0.856	MNN	0.776	SHL	0.555
AQU	0.741	GOL	0.720	MSH	0.602	SLM	0.796
ATL	0.822	GSC	0.682	MUN	0.787	SNG	0.688
ATU	0.728	GUA	0.600	NDI	0.501	STU	0.712
BAG	0.502	HKC	0.520	NHA	0.670	TAB	0.638
BEC	0.857	HLW	0.730	NOR	0.558	TAU	0.711
BKS	0.646	HNR	0.600	NUR	0.520	TOL	0.791
BLA	0.821	HOW	0.608	OGD	0.823	TRI	0.718
BLC	0.802	IST	0.620	ONT	0.805	TUC	0.722
BOZ	0.708	JCT	0.773	PDA	0.832	UME	0.590
CCG	0.631	JER	0.756	PMG	0.567	VAL	0.711
CMC	0.650	KEV	0.525	POO	0.673	WEL	0.601
COP	0.668	KOD	0.713	PTO	0.795	WES	0.823
COR	0.641	KON	0.652	QUE	0.616		
CTA	0.631	LAH	0.571	RAB	0.180	KIP	0.286
DH	0.720	LON	0.655	RAR	0.581	SEO	0.401
DAL	0.782	LPS	0.811	RCD	0.742		

* F, Regional correction factor = −0.22.

Duda $\bar{Q}$ values. In the examples which follow, the m_b values given are those obtained using Duda's $\bar{Q}$ tables.

Seven earthquakes of the Aleutian Islands and mid-Atlantic Ocean were selected for study, to test the theory and methodology developed in this paper. Table 8 presents data for an Aleutian Island, Group 1, earthquake of February 6, 1965. From the table, it can be seen that the $2xy$ factors are less than 0.424 for only five of the 30 stations. Therefore, it is to be expected that the average of the m_b values, and its standard deviation, will be approximately the same for the data of all 30 stations as for the 25 for which $2xy > 0.424$. This expectation is confirmed. The average m_b for all stations listed in the table is 6.28 ± 0.22, whereas, the average of the m_b values corresponding to $2xy > 0.424$ is 6.31 ± 0.24. However, according to our procedure, we must add the regional correction factor, as found in Table 4, of −0.25. This gives a corrected body-wave magnitude of 6.06 ± 0.24.

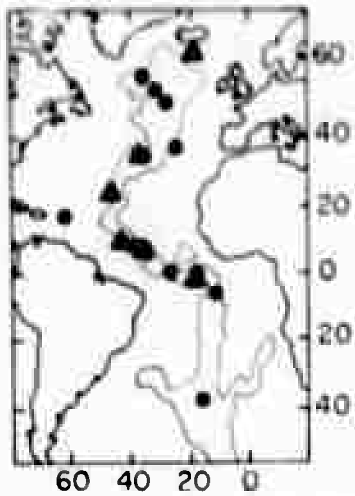

FIG. 3. Epicentral location of mid Atlantic Ocean earthquakes. Group 1 earthquakes, designated by ▲, are of the transform fault type, associated with fracture zones. Group 2 earthquakes, designated by ●, are of the tension type, associated with the ridge.

TABLE 6

$2xy$ AND F^* FACTORS FOR MID-ATLANTIC, GROUP 1 EARTHQUAKES†

Station	$2xy$	Station	$2xy$	Station	$2xy$	Station	$2xy$
AAM	−0.367	LPB	0.359	AKU	0.064	MSH	0.077
ALQ	0.233	LUB	−0.255	AQU	0.193	NAI	−0.027
ANT	0.343	MAL	0.249	ATU	0.180	NDR	−0.098
ARE	0.339	MDS	−0.332	BHP	−0.063	NUR	0.062
ATL	−0.351	MHT	−0.299	BKS	−0.194	PDA	0.042
BEC	−0.459	MNN	−0.321	BOG	0.032	PRE	−0.085
BLA	−0.379	NNA	−0.267	BUL	−0.069	PTO	0.190
BLO	−0.351	OGD	−0.403	CAR	−0.110	QUE	0.070
BOZ	−0.251	OXF	−0.320	CCG	−0.159	QUI	0.107
CMC	−0.205	RCD	−0.278	COP	0.094	SHI	0.090
COR	−0.203	ROL	−0.323	ESK	0.068	SOM	−0.027
DI	−0.271	SCP	−0.398	GDH	−0.187	SPA	0.044
DAL	−0.276	SHA	−0.340	GIE	0.061	STU	0.153
DUG	−0.235	SLM	−0.332	GSC	−0.199	TAB	0.107
FLO	−0.328	TOL	0.218	IST	0.152	TRI	0.369
GEO	−0.399	TUC	−0.213	JER	0.141	TRN	−0.137
GOL	−0.261	WES	−0.414	KEV	0.003	UME	0.039
LON	−0.245			KON	0.059	VAL	0.067
LPA	0.266	AAE	0.074	LPS	−0.139	WIN	−0.124

* F, Regional correction factor = +0.14.

† Latitude 7° to 11°N, longitude 36° to 43°W.

Several comparisons can be made with this last number, namely, the magnitude based on long-period P-wave amplitudes which has been obtained by using the methodology of this paper to correct for the effects of focal mechanism. First, consider m_b based on long-period amplitudes but corrected in an "exact" sense for focal mechanism by means of equation (2), making use of independently determined focal-mechanism parameters. This magnitude is found to be 6.09 ± 0.21, which differs by an insignificant amount from the value above. Second, consider m_b based on short-period amplitudes. For this, we use as data sources the *Earthquake Data Report* of

TABLE 7

$2xy$ and F* Factors for Mid-Atlantic, Group 2 Earthquakes†

Station	$2xy$	Station	$2xy$	Station	$2xy$	Station	$2xy$
AAM	0.851	LON	0.549	AQU	0.039	MSH	−0.040
ALQ	0.731	LPS	0.704	ARE	0.374	NAI	−0.111
ATL	0.842	LUB	0.767	ATU	0.021	NDI	−0.028
BEC	0.729	MDS	0.815	BUL	0.011	NOR	−0.278
BHP	0.610	MUT	0.792	CCG	−0.141	NUR	−0.135
BKS	0.603	MNN	0.780	CMC	0.240	POO	−0.002
BLA	0.860	NNA	0.436	COP	−0.043	PRE	0.018
BLO	0.845	OGD	0.891	GDH	−0.171	QUE	−0.030
BOG	0.524	ONF	0.832	HLW	0.008	SEO	−0.016
BOZ	0.641	QUI	0.522	HOW	−0.004	SHI	−0.017
CAR	0.484	RCD	0.717	IST	0.008	SHL	−0.009
COR	0.555	ROL	0.823	JER	0.005	SOM	−0.114
DI	0.672	SCP	0.876	KEV	−0.248	STU	0.045
DAL	0.799	SHA	0.822	KIP	0.395	TAB	−0.025
DUG	0.668	SLM	0.830	KOD	0.014	TOL	0.009
FLO	0.830	TUC	0.707	KON	−0.145	TRI	0.035
GEO	0.874	WES	0.900	LAH	−0.037	TRN	0.396
GIE	0.587			LPA	0.239	UME	−0.183
GOL	0.727	AAE	−0.004	LPB	0.346	WIN	0.000
GSC	0.658	ANT	0.339	MAL	−0.047		

* F, Regional correction factor = −0.23.
† Latitude 49° to 56°N, longitude 28° to 35°W.

TABLE 8

P-Wave Amplitudes and Magnitudes for February 6, 1965 Earthquake*

Station	Distance (deg)	log A/T	m_b	Station	Distance (deg)	log A/T	m_b
COL	22.6	−0.467	5.99	GEO	69.5	−0.540	6.27
CMC†	35.8	−0.879	5.82	WES†	69.5	−0.698	6.14
NOR†	46.4	−0.628	6.08	HOW†	71.0	−0.493	6.63
GDH†	53.7	−0.549	6.49	COP†	71.7	−0.589	6.23
HKC†	55.3	−0.437	6.34	LAH†	72.2	−0.324	6.50
BAG†	56.0	−0.459	6.29	NDI†	72.8	−0.423	6.44
KEV†	56.3	−0.574	6.48	VAL†	76.0	−0.632	6.2(
KTG†	57.0	−0.734	6.02	QUE†	77.2	−0.344	6.54
MAN†	57.0	−0.404	6.65	STU†	78.8	−0.778	6.08
LUB	59.9	−0.677	6.08	POO†	82.6	−0.311	6.57
DAV†	60.7	−0.525	6.25	IST†	82.8	−0.509	6.37
ONF	66.4	−0.957	5.83	SHI†	84.6	−0.434	6.58
SHL†	66.6	−0.434	6.37	KOD†	87.0	−0.423	6.54
SCP	67.7	−0.521	6.28	TOL†	88.4	−0.656	6.30
KON†	68.0	−0.593	6.24	JER†	89.6	−0.568	6.43

* Time: $4^h02^m52.7^s$.
† Stations for which $2xy > 0.420$, as obtained from Table 4.

the National Ocean Sorvey (NOS) and the *Bulletin* of the International Seismological Centre (ISC). The former gives $m_b = 5.9$, based on the data of 13 stations. The latter gives $m_b = 5.8$, based on the data of 37 stations. Neither publication gives a value of the standard deviation, but all of the data necessary to calculate it are provided. For the ISC magnitude, we obtain a standard deviation of 0.71 and, for the NOS, a

value of 0.28. The latter, however, is misleading, because it was the practice of the NOS to drop all stations whose m_b value differed by more than 0.7 from the average m_b. If these data are not rejected, there are 19 stations, with an average m_b of 5.5; the standard deviation then becomes 0.71.

Finally, the methodology developed in this paper was applied to the short-period P amplitudes, as reported in the *Bulletin* of the ISC. Twelve of the 37 stations for which amplitude data were given for this earthquake are found in the list of stations with $2xy > 0.424$ in Table 1. Using the amplitudes of these stations, and taking account of the regional correction factor, we obtain $m_b = 5.6 \pm 0.57$.

On the basis of all these comparisons, and of similar ones for the other six earthquakes

TABLE 9

SUMMARY OF MAGNITUDE DATA FOR EARTHQUAKES STUDIED

Earthquake	Region	Long Period m_b Values			Short Period m_b Values		M_s
		Uncorrected for focal mechanism	Corrected for focal mechanism: Present method	Corrected for focal mechanism: "Exact method"	NOS	ICS	
Feb. 6, 1965 04h02m52.7s 52.4N, 175.7E	Group 1 Aleutians	6.28 ± 0.22 ($n = 30$)	6.06 ± 0.21 ($n = 25$)	6.09 ± 0.21 ($n = 30$)	5.9 ($n = 13$)	5.8 ($n = 37$)	6 (PAL)
Nov. 22, 1965 20 39 52.0 51.3N, 179.8W	Group 1 Aleutians	6.21 ± 0.29 ($n = 19$)	6.03 ± 0.24 ($n = 17$)	6.01 ± 0.26 ($n = 19$)	5.1 ($n = 12$)	5.0 ($n = 18$)	
July 29, 1965 08 29 21.2 50.9N, 171.4W	Group 3a Aleutians	6.11 ± 0.31 ($n = 52$)	6.24 ± 0.31 ($n = 52$)	6.23 ± 0.30 ($n = 52$)	6.3 ($n = 17$)	6.3 ($n = 13$)	$6\frac{1}{4}$ (PAS)
Feb. 6, 1965 01 40 33.2 53.2N, 161.9W	Group 3a Aleutians	6.98 ± 0.16 ($n = 30$)	6.78 ± 0.16 ($n = 30$)	6.78 ± 0.16 ($n = 30$)	6.4 ($n = 11$)	6.5 ($n = 12$)	$6\frac{1}{2}$ $6\frac{3}{4}$ (PAS)
March 30, 1965 02 27 07.2 50.6N, 177.9E	Group 3b Aleutians	7.20 ± 0.22 ($n = 37$)	7.10 ± 0.18 ($n = 21$)	7.10 ± 0.16 ($n = 37$)	none given	—	7 $7\frac{1}{4}$ (PAS)
Oct. 1, 1965 08 52 04.4 50.4N, 178.2E	Group 3b Aleutians	6.50 ± 0.22 ($n = 46$)	6.35 ± 0.18 ($n = 36$)	6.31 ± 0.11 ($n = 46$)	6.3 ($n = 26$)	—	$6\frac{1}{2}$ (PAS)
Aug. 3, 1963 10 21 30 7.5N, 35.8W	Group 1 mid-Atlantic	6.50 ± 0.26 ($n = 31$)	6.68 ± 0.21 ($n = 15$)	6.93 ± 0.34 ($n = 31$)	6.1 ($n = 8$)		

investigated, we conclude that the standard deviations of m_b obtained from long-period P-wave amplitudes are smaller than those from short-period amplitudes, and that the method of correcting for focal mechanism described in this paper yields essentially the same magnitude and standard deviation as the more exact method based on equation (2). Table 9 summarizes the results for all seven earthquakes.

DISCUSSION AND CONCLUSIONS

Our procedure for correcting body-wave magnitudes for the effect of focal mechanism requires only a few simple steps, which are summarized here. First, determine uncorrected m_b values at all stations for which A/T data are available in the distance range of 25° to 100°. Second, using a table of $2xy$ factors prepared for the hypocentral region, determine if the earthquake's radiation pattern corresponds to that of the dominant

focal mechanism of the region (Syed, Kisslinger and Nuttli, 1971). Third, after verifying that the mechanism of the earthquake corresponds to the dominant one, consult the table of $2xy$ factors to select the stations with $2xy > 0.424$. Find the average of the m_b values of these stations only. Finally, add the regional correction factor, F, to the average of these m_b values. This will give the magnitude of the earthquake, corrected for the focal mechanism.

This procedure in principle can be applied to either short- or long-period body-wave data. We prefer to use the first half-cycle of the long-period P wave for magnitude calculations because it is less influenced by crustal structure at the station than the short-period wave. However, for small magnitude earthquakes, there is no choice, because the P-wave motion is too little to be seen on conventional long-period seismograms. At first glance, it might seem that the practice of using the maximum amplitude in the first three cycles of the short-period P motion will eliminate the need for a focal-mechanism correction, that is, that only the amplitude of the first motion depends upon the radiation at the source. However, Jarosch (1968) used such short-period P-amplitude data to calculate the focal-mechanism parameters, which, as he showed, agreed well with those obtained independently by Stauder, who used long-period data. Therefore, it follows that the maximum amplitude in the first three cycles of the short-period P motion depends upon the focal-mechanism parameters in essentially the same way as the amplitude of the first motion.

A philosophical question can be raised concerning the desirability of correcting the magnitude for the focal mechanism. It might be argued that the magnitude of an earthquake should indicate the amplitude of the motion as recorded at the existing seismograph stations, corresponding to a narrow bundle of rays leaving the hypocenter, rather than the average over the surface of the focal sphere of the amplitude of all of the rays leaving the focus. The answer to the question will depend upon the use which one wishes to make of the magnitude values. If one is concerned with an estimate of the seismic energy, then the focal mechanism correction is appropriate. The correction also is necessary if one wishes to set up an $M_S - m_b$ discriminant between earthquakes and explosions which is as free as possible of regional effects.

In order to apply the present method to earthquakes in geographic regions other than those discussed in this paper, it is necessary to prepare tables of $2xy$ for each such region. To cover all of the seismic regions in the world will require a major effort, because a knowledge of the dominant focal mechanism is required for each such region. However, the work can be lightened somewhat, because, rather than attempt to do focal mechanism solutions for all such regions, one can predict a dominant mechanism for a given region on the basis of plate tectonics and, then, use the amplitude data of individual earthquakes to ensure that the assumed mechanism is consistent with the observed amplitudes. The methods developed in this paper for P-wave magnitudes also can be applied to the correction of S-wave magnitudes for the effect of focal mechanism. We have calculated correction factors, analogous to the $2xy$ factor of P waves, for SH waves for the various subgroups of the Aleutian Islands, Kamchatka, and the mid-Atlantic Ocean. However, we have not yet tested the method with actual SH data because of the rather considerable effort required to obtain such data and because S-wave magnitudes are seldom reported or used in seismicity studies.

Appendix

The factors x and y, which appear in equation (2), are related to the focal-mechanism parameters and the geographical coordinates of the hypocenter and seismograph station by the following equations (Stauder, 1962).

$$x = \alpha_x \bar{x} + \beta_x \bar{y} + \gamma_x \bar{z}$$

$$y = \alpha_y \bar{x} + \beta_y \bar{y} + \gamma_y \bar{z}$$

where

$$\bar{x} = \cos \phi \sin i$$

$$\bar{y} = \sin \phi \sin i$$

$$\bar{z} = \cos i$$

and

$$\alpha_x = \cos AZ_x \cos PL_x$$

$$\beta_x = \sin AZ_x \cos PL_x$$

$$\gamma_x = \sin PL_x$$

$$\alpha_y = \cos AZ_y \cos PL_y$$

$$\beta_y = \sin AZ_y \cos PL_y$$

$$\gamma_y = \sin PL_y \, .$$

In the equations above, ϕ is the azimuth of the ray path at the epicenter toward the station, i is the angle of incidence of the ray at the hypocenter, AZ_x and AZ_y are the azimuths of the force axes of the double-couple system and PL_x and PL_y are the angles of plunge of the force axes.

Acknowledgments

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